Autonomic Function and Exercise Performance in Elite Athletes with Cervical Spinal Cord Injury

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ABSTRACT

WEST, C. R., L. M. ROMER, and A. KRASSIOUKOV. Autonomic Function and Exercise Performance in Elite Athletes with Cervical Spinal Cord Injury. *Med. Sci. Sports Exerc.*, Vol. 45, No. 2, pp. 261–267, 2013. **Introduction**: "Complete" cervical spinal cord injury (SCI) is commonly believed to cause the decentralization of spinal sympathetic circuits and a consequent inability to meet the hemodynamic demands of exercise. Recently, however, we have noticed that athletes with motor complete cervical SCI exhibit an exercise-induced tachycardia that appears to be at odds with the known effects of sympathetic decentralization. **Purpose**: This study aimed to determine the physiological basis of this response and, in doing so, to investigate associations between autonomic function, International Wheelchair Rugby Federation (IWRF) classification, and indices of exercise performance in highly trained athletes. **Methods**: Seven Paralympic wheelchair rugby players with motor complete cervical SCI were firstly classified according to IWRF classification, then assessed for autonomic function (sympathetic skin response [SSR]) and cardiovascular function (systolic blood pressure in response to sit-up tilt). Next, HR_{peak} and distance covered during a field-based maximal 4-min push were measured. Finally, peak oxygen uptake ($\dot{V}O_{2peak}$) and HR_{peak} during laboratory-based maximal incremental arm-crank exercise were measured. **Results**: All athletes demonstrated intact SSR (2.7 ± 1.2 responses from five stimulations), little or no change in systolic blood pressure in response to sit-up tilt (−22 ± 16 mm Hg), and exercise-induced tachycardia (HR_{peak} = 152 ± 20 bpm). SSR was significantly correlated with HR_{peak} in the field, 4-min push distance, and $\dot{V}O_{2peak}$ (all $\rho \geq 0.946$), whereas current IWRF classification was not. **Conclusions**: All participants exhibited partial preservation of descending sympathetic control. We also found that the degree of remaining SSR, but not IWRF classification, was strongly correlated with indices of exercise performance. The findings suggest that the degree of remaining sympathetic control is an important determinant of exercise performance in athletes with cervical SCI. **Key Words:** TETRAPLEGIA, CARDIOVASCULAR, CLASSIFICATION, PARALYMPICS, WHEELCHAIR SPORT

Wheelchair rugby is a Paralympic discipline designed primarily for individuals with cervical spinal cord injury (SCI). During the last 10 yr, there has been a growing scientific interest in the physiological responses of wheelchair rugby players (e.g., 1,13,23,27). This interest most likely stems from the unique physiology of individuals with "complete" cervical SCI; that is, the decentralization of spinal sympathetic circuits, which leaves sympathetic preganglionic neurons below the injury devoid of supraspinal cardiovascular input. The effect of sympathetic decentralization on the exercise response is severe. In uninjured individuals, tonic and reflex activation of the cardiac sympathetic preganglionic neurons causes an exercise-induced tachycardia via the direct stimulatory effect of the cardiac sympathetic neurons on the sinoatrial node. In the absence of sympathetic activity, increases in HR are primarily achieved via the withdrawal of vagal tone, which allows the heart to beat at the internal rate set by the sinoatrial node (approximately 100 bpm [26]). Further increases in HR are achieved via reflex-mediated peripheral spillover of norepinephrine; however, this reflex response is slow and after cervical SCI is reliant on altered sympathetic activity. Thus, the exercise-induced increase in catecholamines is attenuated compared with that in the uninjured population (24). These factors likely explain why HR_{peak} achieved during exercise in individuals with cervical SCI

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Submitted for publication May 2012.
Accepted for publication August 2012.

0195-9131/13/4502-0261/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e31826f5099

rarely exceeds 130 bpm (28). Recently, however, we have noticed that some wheelchair rugby players with neurologically complete cervical SCI regularly reach HRs that far exceed 120 bpm during high-intensity push sessions (unpublished data). Such exercise-induced tachycardia in these individuals appears to be at odds with the known physiological effects of sympathetic decentralization. In an attempt to reconcile this physiological disparity, we investigated whether this exercise-induced tachycardia results from partial preservation of sympathetic control in the face of a neurologically complete cervical SCI.

Since the inception of wheelchair rugby as a Paralympic discipline, the International Wheelchair Rugby Federation (IWRF) method of classification has continually evolved from a simple medical classification to a three-part assessment of motor function, sensory function, and rigorous observational assessment during match play. Motor and sensory assessments in wheelchair rugby are loosely based on the American Spinal Injury Association impairment scale (AIS), which is used in the clinic to assess neurological level and completeness of injury and, consequently, to predict functional outcome of the injury. A potential limitation of these motor- and sensor-centric classification procedures is that remaining autonomic function is not considered. This shortcoming has been recently addressed in the clinical literature by the publication of international standards to document remaining autonomic function in individuals with SCI (2). Unfortunately, no such assessment is included within sporting classification procedures; hence, autonomic assessment has recently been proposed as a "missing part" of Paralympic classification (22).

In light of our observation of substantial exercise-induced tachycardia in cervical SCI and the current IWRF classification method not accounting for remaining autonomic function, we postulate that athletes of similar injury level, with identical sport classification, could have vastly different autonomic function from other competitors. We propose that such differences in remaining autonomic function potentially create an unfair advantage for some competitors. Therefore, the current study aimed to determine the physiological basis of the substantial exercise-induced tachycardia we have witnessed during training sessions and, in doing so, to investigate the associations between autonomic function, IWRF classification, and indices of exercise performance in highly trained wheelchair rugby players with cervical SCI.

METHODS

Participants

Following institutional ethics approval and written informed consent, seven male wheelchair rugby players with motor complete cervical SCI (C6–C7; AIS A and B) volunteered to take part in the study. All participants represented Great Britain at the 2010 Wheelchair Rugby World Cup. None of the participants smoked, had a history of cardiopulmonary disease, or were taking medications known to influence the exercise response. Participant characteristics are shown in Table 1.

Experimental Design

On three separate occasions, participants completed three experimental trials. Trial 1 consisted of motor, sensory, cardiovascular, and autonomic testing. Trial 2 consisted of a maximal 4-min push performance test in the field. Trial 3 consisted of a maximal incremental arm-crank ergometry test in the laboratory. The participants were familiar with all of the testing protocols. Before each trial, the participants were asked to void their bladder to minimize the chance of autonomic dysreflexia (20) and to avoid strenuous exercise for 24 h, caffeine for 4 h, and food for 2 h before assessment.

Methods of Measurement

Trial 1. *Motor and sensory classification.* Motor and sensory classification was performed by one of the study investigators (AK). Neurological classification was conducted using the AIS (19). Briefly, this procedure classifies athletes into one of five categories: motor and sensory complete (AIS A), motor complete and sensory incomplete (AIS B), motor and sensory incomplete (AIS C and D), and normal motor and sensory function (AIS E). In addition, all participants provided their IWRF classification (10). This classification procedure is conducted by an experienced rater and consists of a three-part motor, sensory, and observational assessment.

TABLE 1. Individual participant characteristics.

No.	AIS Scale	IWRF Classification	Age (yr)	Stature (m)	Mass (kg)	Time Post Injury (yr)
1	C7 A	2.5	34.4	1.80	61	16.5
2	C7 A	2	27.8	1.75	63	10.1
3	C7 A	2.5	26.5	1.93	68	2.9
4	C7 A	2.5	34.8	1.75	64	15.3
5	C6 A	1	35.4	1.52	56	13.3
6	C7 B	2	35.2	1.78	77	16.5
7	C7 A	2.5	28.0	1.95	96	11.3
			31.7 ± 4.1	1.80 ± 0.14	69 ± 13	12.3 ± 4.8

Values are for individual participants and group mean ± SD. AIS = American Spinal Injury Association Impairment Scale (A = complete lesion to E = normal); IWRF = International Wheelchair Rugby Federation Classification (0.5 = least function to 3.5 = most function).

Participants are graded in half-point increments from 0.5 (least function) to 3.5 (most function).

Baseline cardiovascular assessment. Participants were instrumented with a one-lead electrocardiogram and a finger plethysmograph (Finonmeter; Finapres Medical Systems BV, Arnhem, the Netherlands) for the beat-by-beat assessment of HR and arterial blood pressure, respectively. An automated blood pressure cuff (Dinamap, GE Pro 300V2, Tampa, FL) was used to calibrate the finger plethysmograph. Supine HR, systolic blood pressure (SBP), and diastolic blood pressure were recorded during 10 min of rest using an analog-to-digital converter (Powerlab/16SP model ML795; ADInstruments, Colorado Springs, CO) interfaced with a computer. Data were stored for subsequent offline analysis (Powerlab version 7.2; ADInstruments).

Orthostatic challenge (sit-up tilt test). Participants rested supine in an air-conditioned room with temperature maintained at 23°C. After 10-min of baseline recordings, HR, SBP, and diastolic blood pressure were assessed during a 10-min sit-up test (7). Briefly, participants were moved to an upright seated position with the legs hanging off the side of the bed at 90°. This "sit-up" position mimics being seated in a wheelchair, except the lower legs and feet are unsupported. Participants were informed as to the importance of this procedure being passive and were instructed to not assist in the "sit-up" procedure. Orthostatic hypotension (OH) was defined as ≥20 mm Hg drop in SBP on assumption of the upright position (8). The test was terminated prematurely if the participant exhibited signs of presyncope. HR and blood pressure data were averaged for 30-s intervals, and the largest drop in blood pressure was used to define the presence or absence of OH.

Sympathetic skin response. After completion of the sit-up test, the participants were returned to the supine position for a rest period of at least 10 min, or until blood pressure returned to resting baseline. Sympathetic skin responses (SSR) were then obtained by electrical stimulation of the median nerve at the wrist. Self-adhesive recording electrodes were applied bilaterally to the palmar and dorsal cervices of the hands and feet. SSRs were recorded simultaneously from both hands and feet for 8 s and sampled at a band-pass filter of 3 Hz to 3 kHz. Five recordings with stimulations (duration, 0.2 ms; intensity, 10–20 mA) at each site were obtained. Responses were quantified by the number of SSRs elicited at each site (6,21), and the mean across all four sites was reported. Hence, for each site, the maximum score would be 5, whereby all five stimulations elicit a response. To minimize the well-known habituation and adaptation of these responses, stimuli were applied with variable time delays (≥90 s). A SSR was deemed present when there was a clear positive deflection from baseline that occurred after a typical delay (~2.0 s) after stimulation (Fig. 1). Any potential that coincided with muscle spasm, limb movement, or cough was excluded from the analysis. Data were continuously collected using an analog-to-digital converter (Powerlab/16SP model ML795; ADInstruments) interfaced with a computer and stored for subsequent offline analysis (Powerlab version 7.2; ADInstruments).

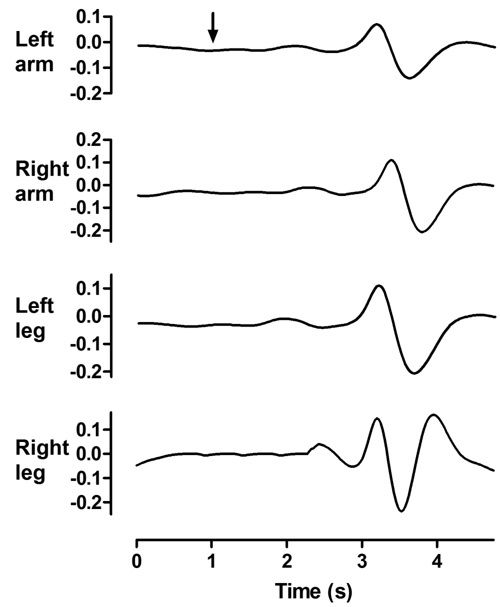

FIGURE 1—Example tracing of a preserved sympathetic skin response to median nerve stimulation. Arrow denotes point of stimulation. Note that a response was elicited at all four sites despite this individual being classified as an AIS A (complete motor and sensory injury) and an IWRF grade 2.0.

Trial 2. Participants completed a sports-specific 4-min maximal push on a 140-m straight synthetic track. Markers were placed every 2.5 m to enable distance to be recorded to the nearest 2.5 m. HR was measured via telemetry (Suunto team POD; Suunto Oy, Vantaa, Finland). HR_{peak} was defined as the highest HR averaged for a 30-s period. Before testing, participants performed a 10-min standardized warm-up comprising of short pushes (self-selected pace) and upper-body static stretches as per their normal warm-up routine before a training session.

Trial 3. Participants performed maximal incremental arm-crank exercise (5 W every 2 min, 60–70 rpm) on a computer-controlled electromagnetically braked arm ergometer (Angio; Lode, Groningen, the Netherlands). The arm ergometer was set so that the scapula–humeral joint and the distal end of the crank pedal were aligned. When necessary, the hands were fixed to the handles with a gripping aid commonly used by the participants during their normal training (Active Hands, Woodley, UK). Starting intensity was based on functional classification and ranged from 20 to 45 W. Exercise was continued until failure to maintain a cadence >50 rpm. Oxygen uptake ($\dot{V}O_2$) was measured using an online system (Oxycon Pro; Jaeger, Höchberg, Germany), and HR was measured via a telemetric monitoring system (Polar Vantage NV; Polar Electro Oy, Kempele, Finland). $\dot{V}O_{2peak}$ and HR_{peak} were defined as the highest $\dot{V}O_2$ and HR averaged for a 30-s period, respectively.

BASIC SCIENCES

TABLE 2. Individual participant results.

No.	Baseline CV Parameters		Response to Sit-Up Test		OH	Mean SSR	Field Test		Laboratory Test	
	BP (mm Hg)	HR (bpm)	ΔSBP (mm Hg)	ΔHR (bpm)			4-min Push Distance (m)	HR_{peak} (bpm)	$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	HR_{peak} (bpm)
1	117/67	50	−16	7	−	2.8	710	158	20.2	113
2	116/56	54	−16	11	−	5.0	775	178	23.0	138
3	105/65	49	−11	23	−	3.0	850	172	22.6	132
4	95/60	58	−29	27	+	2.8	715	156	21.4	128
5	84/55	69	−10	0	−	1.0	685	121	12.1	100
6	100/58	39	−15	5	−	2.3	700	141	19.9	123
7	121/73	65	−56	12	+	2.3	705	135	16.7	124
	105/62 ± 13/6	62 ± 7	−22 ± 16	12 ± 9		2.7 ± 1.2	734 ± 58	152 ± 20	19.4 ± 3.80	123 ± 13

Values are for individual participants and group mean ± SD. CV = cardiovascular; BP = blood pressure; SBP = systolic blood pressure; OH = orthostatic hypotension; − denotes no OH present; + denotes the presence of OH; SSR = sympathetic skin response.

Statistics

Associations between outcome measures were assessed using Spearman's rank correlation coefficient. The 95% confidence intervals (CIs) around the correlation coefficients were created using Fisher's z transformation. Differences in HR_{peak} in the field and laboratory were analyzed using a paired samples t-test. Statistical analyses were performed using the Statistical Package for the Social Sciences for Windows (Version 16.0; SPSS Inc., Chicago, IL). Statistical significance was set at $P < 0.05$.

RESULTS

Resting autonomic and cardiovascular function. Individual data for resting and performance variables are presented in Table 2. Four participants exhibited resting hypotension (supine SBP < 110 mm Hg) and five participants exhibited resting bradycardia (HR < 60 bpm). In response to the sit-up tilt test, only two participants met the criteria for OH, and all individuals exhibited some preservation of SSR (see also Fig. 1), despite having been classified as AIS A (n = 6) or AIS B (n = 1). The degree of SSR preservation was variable among all participants and ranged from minimal preservation (participant 5) to full preservation (participant 2). The participant with the greatest preservation of SSR held an AIS classification grade A and an IWRF classification of 2.0.

Associations between outcome variables. The average number of SSRs obtained across all four sites was strongly correlated with HR_{peak} in the field (ρ = 0.982, 95% CI = 0.865 to 0.995, P < 0.001), 4-min push distance (ρ = 0.946, 95% CI = 0.665 to 0.990, P = 0.001), and $\dot{V}O_{2peak}$ (ρ = 0.982, 95% CI = 0.865 to 0.995, P < 0.001) (see also Fig. 2). Conversely, IWRF classification was not significantly correlated with HR_{peak} in the field (ρ = 0.233, P = 0.49), 4-min push distance (ρ = 0.467, P = 0.17), or $\dot{V}O_{2peak}$ (ρ = 0.233, P = 0.49). There was no association between the average preservation of SSR and the IWRF classification (ρ = 0.365, P = 0.421). HR_{peak}, 4-min push distance, and $\dot{V}O_{2peak}$ were strongly correlated with each other (all $\rho \geq 0.893$, P < 0.01). HR_{peak} during the maximal 4-min push test exceeded HR_{peak} in the laboratory in all participants (P = 0.001).

DISCUSSION

We report for the first time that elite wheelchair rugby players with motor complete cervical SCI exhibit partial preservation of spinal sympathetic circuits, as evidenced by a partially intact SSR to median nerve stimulation. Furthermore, the degree of remaining SSR is strongly correlated with indices of exercise performance, including 4-min push distance, HR_{peak}, and $\dot{V}O_{2peak}$. We also demonstrate that

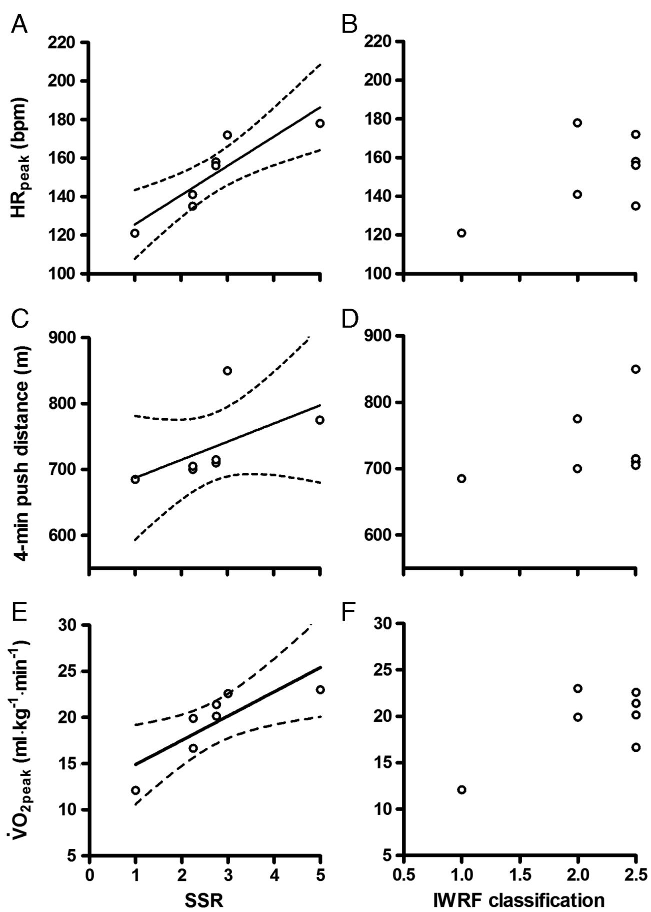

FIGURE 2—Associations between sympathetic skin response (SSR), IWRF classification, and indices of exercise performance. Note that SSR was strongly correlated with all performance outcomes (panels A, C, and E), whereas IWRF classification was not (panels B, D, and F). Broken lines denote 95% CI.

HR_{peak} is substantially higher in a field-based exercise test compared with a laboratory-based arm-crank exercise test.

After a neurologically complete cervical SCI (AIS A), it is a commonly held belief that all such individuals lose supraspinal input to the spinal sympathetic circuits and are therefore unable to cope with the significant hemodynamic challenges imposed by exercise. We reject this notion by demonstrating that a group of Paralympic athletes with motor complete cervical SCI all exhibited some preservation of supraspinal input to the spinal sympathetic circuits. We also found that only two participants exhibited OH on assumption of the upright posture and that all participants demonstrated substantial exercise-induced tachycardia. The combination of a partially intact SSR, little or no orthostatic hypotension, and exercise-induced tachycardia provides compelling evidence that the participants in the current study exhibited partially preserved descending sympathetic cardiovascular control. This is different from what is typically observed in the general SCI population, where most of those with a neurologically complete cervical SCI exhibit little or no SSR to median or tibial nerve stimulation (7). Although we have no statistical comparisons between participants with chronic SCI and the athletes in the current study, the apparent difference implies that partial preservation of sympathetic control after neurologically complete cervical SCI is not only possible but is perhaps an important determinant of exercise performance at the Paralympic level.

Perhaps the most important findings of the current study were the strong positive correlations between SSR and HR_{peak}, 4-min push distance, and $\dot{V}O_{2peak}$. In the nondisabled population, it is well accepted that exercise performance is intimately linked to autonomic cardiovascular function. Although previous findings of an enhanced exercise capacity via boosting (a nociceptive stimulus, usually via restriction of urinary outflow) have implicated autonomic cardiovascular control as an important determinant of exercise performance in SCI (5), the current study is the first to directly test this postulate. Our finding of a strong correlation between SSR and all indices of exercise performance provides strong evidence that the degree of sublesional sympathetic control is an important determinant of exercise performance in athletes with cervical SCI. Conversely, we did not find a significant correlation between the IWRF classification and the remaining sympathetic control. Given the importance of the sympathetic nervous system to the exercise response, it is perhaps unsurprising that we also found no significant associations between the IWRF classification and the maximal 4-min push distance, $\dot{V}O_{2peak}$, or HR_{peak}. This may be an anomaly of the statistical technique as we had four participants with the same IWRF classification, but therein lies the problem: participants can share the same IWRF classification yet perform markedly different in meaningful assessments of exercise performance. For example, participant 2 (IWRF classification 2.0) had a greater preservation of SSR, a higher $\dot{V}O_{2peak}$ and a higher HR_{peak} than all the participants with an IWRF classification of 2.5. Partial preservation of sublesional sympathetic control for the athletic SCI population should not be underestimated and is likely to create a distinct sporting advantage. During exercise, an athlete with a partially intact sympathetic nervous system would be expected to exhibit enhanced cardiac chronotropy, increased circulating catecholamines, improved blood redistribution capability, and superior thermoregulation compared with those with complete loss of supraspinal sympathetic control (28).

The highest individual HR_{peak} recorded in the 4-min push test was 178 bpm, with a group mean HR_{peak} of 152 ± 20 bpm. To the authors' knowledge, these HRs are the highest reported in individuals with motor complete cervical SCI. The temporal robustness of the HR response to exercise combined with partial preservation of SSR provides evidence of axonal sparing of descending sympathetic pathways in the face of a neurologically complete SCI. Axonal sparing after neurologically complete SCI is by no means a new phenomenon (e.g., 3,4,14,16). Indeed, up to 65% of individuals with an AIS grade A exhibit a zone of partial preservation, meaning there is some axonal sparing across the lesion site (4). Using histopathological techniques, we have also documented that even in individuals with a severe neurological injury, there is partial preservation of descending cardiovascular (autonomic) pathways within the spinal cord, and that this correlates with the severity of the cardiovascular dysfunction observed clinically (12). Data from the current study confirm these findings and provide definitive evidence that neurological completeness of injury does not correlate with autonomic completeness of injury. On the contrary, we found full preservation of SSR responses across all four sites in a participant with a C7 AIS grade A (Fig. 1). This is hardly surprising as the AIS does not account for remaining autonomic function. Thus, in agreement with previous suggestions (7), we advocate the use of autonomic testing as a supplement to the current AIS examination.

When HR_{peak} was assessed during arm-crank exercise, the values obtained were much lower than during the field-based assessment and in agreement with typical values reported in the literature for HR_{peak} in individuals with cervical SCI (9,11,13,17,24,27,29). This is not the first time that such discrepancies in HR_{peak} have been found between laboratory- and field-based exercise testing (18). HR_{peak} achieved during maximal wheelchair propulsion on a treadmill has been reported to be similar to that in arm-crank exercise in individuals with chronic SCI (15,25), a finding we too have anecdotally noticed in athletes. Thus, we do not believe a difference in exercise modality explains our findings. Neither do we believe that cardiovascular drift explains these high HR_{peak} values because the field test lasted only 4-min and all participants reached HR_{peak} within the first minute. Rather, we believe that athletes are simply more accustomed to pushing in the field and are able to choose (and regularly change) their push technique during field-based assessments. This is different to the laboratory, where the stringent protocols coupled with the testing modality

BASIC SCIENCES

(wheelchair propulsion on a treadmill or arm-crank exercise) do not accommodate such deviations in push technique. Unfortunately, no study has investigated differences in push biomechanics between laboratory and field testing in athletes with cervical SCI. Until such studies are carried out, care must be taken when extrapolating results from laboratory-based exercise testing to field-based sport performance.

A potential limitation of the current study is that only seven participants were tested. To minimize the degree to which sample size affected our correlations, we calculated 95% CIs for each correlation coefficient. The lower 95% CIs obtained for average SSR score versus the three indices of exercise performance all exceeded 0.66. Thus, we are confident in our interpretation that strong relationships exist between remaining sympathetic control and meaningful indices of exercise performance. That said, a large-scale study investigating the link between exercise performance, remaining sympathetic control, and current IWRF classification is needed before evidence-based recommendations for the addition of autonomic testing can be made. Nevertheless, the data presented in the current study provide further credence to the notion that autonomic assessment is a "missing part" of Paralympic classification (22).

In conclusion, Paralympic athletes with cervical SCI exhibit partial preservation of SSR, little or no OH, and substantial exercise-induced tachycardia. These results suggest that partial preservation of descending autonomic control to sublesional sympathetic circuits may be an important determinant of exercise capacity and wheelchair rugby performance. We also demonstrate for the first time that the degree of remaining SSR is strongly correlated with functional indices of sports performance, whereas IWRF classification is not. That all individuals exhibited some preservation of descending autonomic pathways in the face of motor complete SCI suggests that autonomic testing should be considered in the classification procedure of athletes with SCI at or above the T6 spinal level.

This study was partially supported by the Canadian Foundation for Innovation and the British Columbia Knowledge Translation Fund (PI Dr. Andrei Krassioukov).

The authors declare no conflict of interest. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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